An Accelerated History of the Universe

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Abstract. The past decade has ushered in a revolution in our understanding of the Universe. In broad brush, we summarize how a series of observations have led to four key cosmological realizations. These realizations then lead to a standard model of cosmology somewhat different from what might have been expected even just a decade ago. In addition, we have gone from being unsure about qualitative features of the Universe to arguing about percent-level details of the model. It has been a truly remarkable transition.

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INTRODUCTION

Unless you've been hiding in a cave, recent developments in cosmology have been inescapable. There have been tremendous observational advances in the field, revolutionizing much of our understanding of the Universe we live in. Fifteen years ago there were great debates over the geometry and composition of the Universe. Now, we are in an era of precision cosmology, where reasonable people argue over ten percent values in fundamental quantities. Even more shocking, the current cosmological standard model is not one of the serious contenders from a decade ago. In some sense, all of these developments can be boiled down to four key points:

- the Universe is (very close to) spatially flat
- the baryonic content of the Universe, alone, is insuficient to account for the total matter content
- the total matter content of the Universe, alone, is insufficient to attain spatial flatness
- the expansion of the Universe is accelerating

When taken together, these lead to some startling conclusions. These in turn can be summarized:

- Conventional, every-day matter (i.e., baryons) makes up only $\sim 1/5$ of the total matter density of the Universe. The rest is "dark matter".
- Baryonic and dark matter, together, only contribute $\sim 1/3$ of the total energy density of the Universe. The rest is "dark energy". The dark energy component dominates our Universe, and governs its present evolution.
- The sum total energy density is consistent (at the few percent level) with the critical value needed to "flatten" the Universe.

This article is a summary of a “Hot Topics” talk, aimed at graduate students attending the PANIC conference. This is not a formal review article, and I have taken some liberties with historical progression and technical content. I have also neglected huge swaths of the field (including details of big bang nucleosynthesis, cosmic microwave background radiation, baryon acoustic oscillations, and structure formation). At the end of the article I have listed a number of reference texts, which include much more detailed discussions, and are good starting points for further exploration of the field. They also include appropriate references to the original work, both theoretical and observational, that I am woefully neglecting.

UNDERPINNINGS

Modern physics can be split into two theories: general relativity and quantum mechanics. The former governs everything big (Earth, Sun, and on up), while the latter governs the small stuff (protons, electrons, photons). Of course, there are regions of overlap. And more importantly, the two theories are in some sense fundamentally incommensurate. We are hopeful that a theory of quantum gravity will arise to unify all forces. String theory may fulfill this dream. Then again, it may not.

Cosmologists take as their subject of study the entire Universe. This means everything that we can observe, on the largest scales, is our purview. Needless to say, this implies that general relativity is of paramount importance, and forms the underlying basis of modern cosmology. It provides the (dynamic) stage upon which the rest of cosmology is played out. It is to be emphasized that the Universe started out small and hot and dense. Thus quantum mechanics becomes important in the first few minutes of the Universe’s existence. Going back to even earlier times (10^{-43} seconds), the Universe becomes small enough that the quantum mechanics of the system itself becomes important, at which point a full theory of quantum gravity is required. It turns out that details of these earliest times can be encapsulated in a simple set of initial conditions, allowing us to model precisely the ensuing billions of years of cosmological evolution.

We can make a few important generalizations about the connection between gravity and the Universe, without the full apparatus of general relativity. We know the Universe is full of gravitational matter: we see it all around us (ourselves included). We also know that gravity only attracts (there is no anti-gravity), and that gravity cannot be shielded (unlike electromagnetism). Every object, no matter how small (e.g., an electron) exerts a force of attraction on everything else in the Universe. Of course, for nearby things, the electron’s electromagnetic force can be much stronger. But at large (cosmological) distances, its electromagnetic force is screened, and all that is left is a net gravitational force.[1] The moral is that every object in the Universe gravitationally attracts every other object.

Now let us construct a simple-minded model for the Universe. We’ll assume that on large scales the Universe is homogeneous and isotropic. This is a fancy way of saying

[1] Technically this is only true within the past lightcone of the electron. This becomes a restriction because of the Universe’s finite age.

that not only are we not in a special place in the Universe, but that no such place exists, nor does there exist a preferred direction. As a rough approximation, let's just place galaxies on an equally spaced grid, extending arbitrarily in all three spatial directions. We'll take the grid to be stationary, so that the galaxies just sit there. Furthermore, we'll assume that the galaxies have been there forever, immutable. This seems like a good first attempt at a model of the Universe. It is more sophisticated than pre-Copernican models (which had the Earth at the center), and allows us to adjust the scale (the spacing of the grid), as well as the objects at the vertices (stars, or galaxies, or clusters).

It follows directly from our simple gravitational arguments above that our cosmological model is fundamentally flawed. Consider any particular galaxy. It is exerting an attractive gravitational force on all other galaxies. This cannot be screened. Thus, over time, all other galaxies in the Universe must accelerate towards it. This is true for each and every galaxy. Thus, we conclude that *the Universe cannot be static*. Although it might appear static at some point, this situation cannot possible remain stable.

Furthermore, our simple-minded model, when combined with basic notions of gravity, tells us that *the Universe's expansion must be decelerating*. Although the distance between galaxies might be increasing with time, the rate of this increase must be decreasing.

Let us take R to be the average distance between galaxies. We have thus arrived at the following:

$$\frac{d^2R}{dt^2} < 0, \tag{1}$$

where t is time. This states that the Universe's expansion must be decelerating. From this, we also conclude that, in general, the expansion rate must be nonzero. The Universe might be expanding ($\dot{R} > 0$) or contracting ($\dot{R} < 0$), but it can only be static ($\dot{R} = 0$) for an instant.

These statements remain true in the general theory of relativity. When Einstein first realized this, the concept of a dynamical Universe was incredibly radical. And, furthermore, it was not indicated by observations (which were of quite limited scope at that time). Einstein thus introduced into his theory the *Cosmological Constant*. It is to be emphasized that this was the last and only possible generalization to his theory. Although it smacks of a fudge factor, it is in some sense a required term if one is to truly write down the most general local, coordinate-invariant, divergenceless, symmetric, two-index tensor theory. By tuning this constant to an appropriate value, Einstein found it possible to engineer a Universe where all the galaxies stayed put, so that $\dot{R} = \ddot{R} = 0$. It is to be noted that this "Einstein static Universe" is not stable. Although the finely tuned configuration is static, any perturbations to it will cause the Universe to become dynamic. One extra electron, and eventually that part of the Universe will collapse.

About a decade later Hubble discovered that other galaxies appear to be moving away from us, and that the Universe indeed appeared to be expanding. This revolutionary idea was a natural outgrowth of relativity. There was no need for Einstein's cosmological constant, and it was ignominiously discarded.[2]

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[2] This was purported to have been dubbed by Einstein his biggest blunder. To some extent, it was. Imagine if Einstein had *predicted* that the Universe was dynamic. This would have been one of the greatest

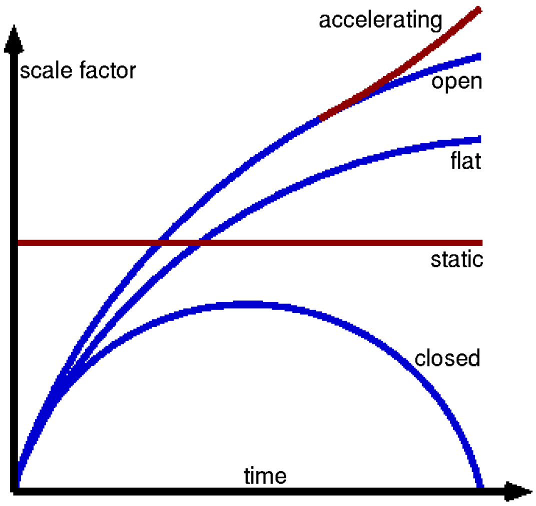

FIGURE 1. A sketch of the possible evolution histories of the Universe. Current observations indicate that we live in a Universe suffering accelerated expansion: the very top curve in the Figure.

Without the cosmological constant, there are qualitatively three possible Universes. If the matter density is below a critical value (given by $\rho_{\rm crit} = 3H_0{}^2/8\pi$, where $H_0 = \dot{R}/R$ is the Hubble constant), then the Universe expands forever. This is an “open” universe, with hyperbolic spatial sections. The deceleration, which decreases as the Universes gets less dense due to the expansion, cannot overcome the inital expansion from the big bang. If the matter density is above the critical density, then the Universe’s expansion eventually halts, and from then on the Universe collapses, eventually ending in a big crunch. This is a “closed” Universe, with spherical spatial sections. If the density is tuned to the critical value, then the Universe exands forever, continually decelerating, and never quite reaching zero expansion velocity. This is a Universe with flat spatial sections.

The addition of the cosmological constant changes this somewhat. It allows for a static Universe, as well as accelerating Universes. In the latter case, the energy density due to the cosmological constant eventually dominates (as the matter density continues to drop as $1/R^3$ and the radiation density drops as $1/R^4$, while the cosmological constant has constant density). Once the cosmological constant dominates, the expansion of the Universe begins to accelerate. The possible evolution histories of the Universe are shown in Figure 1.

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predictions ever accomplished by science. For millenia humanity had labored under the paradigm of an immutable Universe. Through abstract thought and reasoning alone, combined with modest observations, Einstein could have completely overthrown this paradigm.

OBSERVATIONS

CMB

One of the observational pillars of modern cosmology is the Cosmic Microwave Background (CMB). Its mere existence is resounding confirmation of the standard big bang cosmology. As we go back in time the Universe gets smaller and denser and hotter. At some point the Universe gets so dense that electrons are stripped from their atoms, and the resulting hot plasma is opaque to photons. After this point (which is roughly 400,000 years after the big bang) the photons free stream all the way to us today (at roughly 14 billion years after the big bang), and leave an imprint of the Universe at that early time.

What we see today is an exquisitely smooth black body at roughly 2.7 Kelvin. There are tiny fluctuations in this temperature, at roughly one part in 100,000, in different parts of the sky. These are related to perturbations from the very early Universe, which cause both the dark matter and the baryons to form clumps as gravity takes over. Detailed observation of the temperature anisotropy offers strong constraints on cosmological parameters. Physics in the early Universe determines a preferred scale. By observing features in the CMB today, the observed and intrinsic scales can be compared, and their relation depends sensitively on cosmological parameters. The recent Wilkinson Microwave Anisotropy Probe (WMAP) has provided beautiful measurements of this fluctuation spectrum. The most important constraint from CMB is that the Universe is very close to flat: the total energy density is within a few percent of the critical density.

Supernovae

Another important observational underpinning of modern cosmology is the Hubble diagram, which encapsulates the evolution history of the Universe. The Hubble diagram is a plot of the luminosity-distance of objects, as a function of redshift. Luminosity-distance is a measure of distance, and for any given object is thus a measure of the age of the object. The light from the object must have travelled at the speed of light. If we know its distance, we know how long ago that light must have been emitted, and hence its age. The redshift of a given object is directly related to the ratio of the size of the Universe at the time of emission from that object to the size of the Universe at the time of observation (i.e., today). Thus observation of redshift is an observation of the scale of the Universe. Putting these together, observation of the luminosity-distance curve is a measure of the size of the Universe as a function of time: the evolution history of the Universe.

We use type Ia supernovae to measure the luminosity distance–redshift curve. We believe we can calibrate the intrinsic brightness of these supernovae to roughly 15%, and thus can use them as standard candles. By observing a supernova at high redshift, and knowing its intrinsic luminosity, we can figure out how much the supernova has been dimmed, and hence directly measure its luminosity distance. This has been done successfully by a number of observational groups, yielding a detailed Hubble diagram.

The observed supernova Hubble diagram constrains the Universe to be suffering accelerated expansion. There is no way for the supernovae to be as dim as they are at high redshift ($z \sim 1$) without them having been dimmed due to a larger-than-expected Universe due to cosmic acceleration. This discovery, in 1998, led to the current revolution in cosmology.

CONCLUSIONS

Combining the supernova and CMB measurements, and a host of other consistent observations (including the baryon acoustic oscillations, weak lensing, the matter power spectrum, big bang nucleosynthesis, etc.) we arrive at a self-consistent "concordance cosmological model", with the main observational features listed above. It is this model that cosmologists are busily exploring and trying to further constrain. We are left with a couple of outstanding mysteries. Put simply:

- What is the dark matter?
- What is the dark energy?

There are a number of proposals for the existence of particles that could account for the dark matter, and there are active experimental and observational programs searching for these candidates. Unfortunately, parameter space is *large*, and it is easily possible that the dark matter will not be seen in the foreseeable future. Although it would be particularly satisfying to detect it directly in a laboratory (or at a particle accelerator), there are many independent reasons to believe the dark matter exists.

The dark energy poses a much more challenging observational and theoretical problem. Theorists are pretty much at sea as to why it should be found at such a small, but nonzero, value. Perhaps it is a true cosmological constant (implying constant energy density, despite the Universe's expansion)? Perhaps it is a dynamical quantity, with changing density (both in space and time)? We are currently clueless, and a great part of future observational and theoretical work will address the nature of the dark energy. These questions are of particular interest as they may well relate to underlying fundamental physics, and could therefore shed light on quantum gravity.

What is probably most remarkable is that we understand the Universe at all. Theorists blithely apply the theory of general relativity to scales many orders of magnitude beyond anything we've been able to directly probe, and at times billions of years earlier than today. And yet the theory works flawlessly, explaining an astounding range of observations with a small number of basic parameters. It is a truly amazing accomplishment, of which physicists are justly proud. On the other hand, 95% of the energy density of the Universe is in a dark form that we have not managed to directly observe, nor have we managed to theoretically explain. So there is much, much work yet to be done!

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REFERENCES

1. S. Carroll, *Spacetime and Geometry: An Introduction to General Relativity*, Addison Wesley, 2003
2. E. W. Kolb & M. S. Turner, *The early universe*, Westview Press, 1990
3. E. V. Linder, *First Principles of Cosmology*, Addison-Wesley, Essex, 1997
4. P. J. E. Peebles, *Principles of Physical Cosmology*, Princeton University Press, 1993